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A Cost Modeling of High-Capacity LTE-Advanced and IEEE 802.11ac based Heterogeneous Networks, Deployed in the 700 MHz, 2.6 GHz and 5 GHz Bands

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Abstract

In this paper we develop “state-of-the-art” cost model of the heterogeneous wireless networks in order to determine the most cost effective radio network deployment as a function of extreme demand levels of more than 100 GB per user and month. We perform comparative analysis by consideration of the advanced radio access technologies like LTE-Advanced and IEEE 802.11ac Wi-Fi standard. Our analysis especially contributes to the assessment of the benefits when operating LTE-Advanced technology on the forthcoming “Digital Dividend II” band. The outcome of the cost model gives the proper assessment of the total investment needed to serve certain area, using bands ranging from 700 MHz and up to 5 GHz. The key finding is that the small cell solutions, like femto cells and Wi-Fi, are more cost efficient when new macro base station sites need to be deployed or when very high demand levels need to be satisfied. In all other evaluated cases, results show that the importance of the spectrum size is significant in leveraging cost-capacity performance. By evaluating the economic value of a joint deployment of small and macro cells, we determine that instead of investing in additional spectrum or deploying denser network, mobile operators could compensate the indoor wall penetration losses by femto or Wi-Fi sites.

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1. Introduction

The forthcoming wireless network architectures become more heterogeneous, with base stations (BS) sites/cells ranged as follows: macro (MaBS), micro (MiBS), pico (PBS) and femto (FBS) complemented with particular wireless local area network (WLAN/Wi-Fi). Analysis of MaBS, MiBS and PBS HSPA cells capacity-

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cost comparisons including IEEE 802.11a, are provided in [1, 2]. Cost comparisons of LTE with HSPA deployed MaBS and FBS solutions are covered in [3, 4]. The evaluation of the economic gain of FBS and MaBS for LTE RAT is outlined in [5]. In all researches [1-5], the frequencies used are at 800 MHz band or above.

In this article we originally introduce the comparative cost modeling of MaBS, MiBS, PBS and FBS utilizing the capacity and coverage parameters of Long Term Evolution Release 10 or LTE-Advanced (LTE-A) radio access technology (RAT) [6, 7], alongside with Wi-Fi standard IEEE 802.11ac [8], also considering the performance of the 700 MHz band. As according to [9], more than 80% of the mobile traffic is generated in indoors, we create long-term investment case study related to servicing the indoor office users. In order to determine more realistic cost-capacity performance modeling, besides the wall attenuation and indoor coverage strategies covered in [3, 4], additionally we consider the carrier aggregation functionality of LTE-A. We also assess the economic gains of joint deployments by the consideration of the total discounted costs.

The paper is structured as follows. Sections 2 and 3 describe the analysis approach through elaboration of RAN specific coverage, capacity and unit cost estimates for various BS classes deployed with advanced RATs. In the next section we perform investment modeling of various wireless network deployments through the case study. In section 5 we discuss the findings and analyze the most and less cost-effective separately deployed scenarios and we demonstrate the benefits of the combined cost-capacity modeling of different wireless solutions to satisfy high demand levels. A conclusion is found in section 6.

2. Coverage and Capacity Modeling

Based on [10], a BS of class i is characterised by a maximum average throughput or capacity T_{maxi} and cell range r_i related to coverage. We model the coverage A_{cell} of particular cell area of the BS site i as follows:

$$A_{cell} = \pi \cdot r_i^2 \quad (1)$$

Based [11, 12] the urban cell range varies from 0.6 km at 2.6GHz to 1.4 km at 900 MHz (wall penetration losses (20 dB)). According to [3, 4] we consider 0.57 km range for MaBS in the urban dense area. Based on [1, 2], we estimate 0.27 km for MiBS and 0.1 km range for PBS. FBS cell range in [3] is assumed to be 0.050 km and in [13] in range of 0.01 – 0.030 km. According to [14], we model the system capacity, T_{syst} , as follows:

$$T_{syst} = W \cdot N_{site} \cdot N_{cell} \cdot S_{eff} \quad (2)$$

where W is allocated bandwidth in MHz, N_{site} is the total number of BS sites, N_{cell} is the number of cells, and S_{eff} is the average cell spectral efficiency in bps/Hz/cell. Based on [6, 7] the average spectral efficiency for LTE-A varies from 6.6, 4.2 and 3.8 bit/s/Hz/cell for the indoor, microcellular and base coverage urban environments [15], respectively. We consider FBS deployment in a different frequency band than MaBS to cope with the interference problems to non-FBS cells [16, 17]. According to [13, 18], we use the 20 MHz of spectrum for FBS with 50 m coverage range. According to [19, 20], it is very difficult to exceed 50-60% of the nominal bit rate of the underlying physical layer of Wi-Fi. According to [21], we consider the first-wave IEEE 802.11ac products operating in the 5 GHz band with 80 MHz and delivering up to 1300 Mbps at the physical layer up to 30 m coverage range. In Table 1, we summarize the coverage and capacity estimates related to different BS classes.

3. Cost Modeling

We perform the cost structure modelling according [1, 5] by limiting to the capital investment to acquire and deploy the RAN (CAPEX), and the costs to operate the RAN (OPEX). We consider the BS equipment, BS site installation, backhaul transmission equipment and radio network controller (RNC) equipment as BS related CAPEX items, as well as the electric power, operation & maintenance, site lease and backhaul transmission lease as BS related OPEX items. Also we evaluate the CAPEX and OPEX of the system spectrum. According to [22] an even more accurate model could be obtained by using present values instead of annualizing the CAPEX.

Table 1. Radio Access Network – Coverage and Capacity Parameters.

LTE-A BS and IEEE 802.11ac AP Parameters	MaBS	MiBs	PBS	FBS	Wi-Fi
Range (km)	0.57	0.25	0.10	0.05	0.03
Coverage (km ²)	1.02	0.19	0.03	0.008	0.003
Sectors	3	1	1	1	1
Carriers	1 – 3	1 – 2	1	1	1
Cells	3 – 9	1 – 2	1	1	1
Bandwidth (MHz)	20	20	20	20	80
Av. Cell SE (bps/Hz)	3.8	3.8	6.6	6.6	16.25
Av. Cell Capac.(Mbps)	76	76	132	132	1300
Av. Site Capac. (Mbps)	228	76	132	132	1300

In order to calculate the cost per item of type i in present value, according to [2] we use the standard method for cumulated discounted cash flows for the whole network life cycle (K years) as follows:

$$\mathcal{E}_i = \sum_{k=0}^{K-1} \frac{a_{k,i}}{(1+\beta)^k} \quad (3)$$

where $a_{k,i}$ is the sum of expenditures, occurred within year k of an item of type i and β is the discount rate. In all analyzed scenarios in this paper we assume network life cycle of $K = 10$ years. Further, according to [5], we use the discounted rate equalized to the weighted average cost of capital (WACC) of $\beta = 12\%$. Hence, the total discounted cost, C_{TOT} , of a wireless heterogeneous network normalized per unit of area is:

$$C_{TOT} = \mathcal{E}_M \cdot N_M + \mathcal{E}_S \cdot N_S + \frac{\mathcal{E}_{SPECTRUM}}{A_{syst}} [cost/area] \quad (4)$$

where \mathcal{E}_M is the total discounted cost of MaBS, \mathcal{E}_S the total discounted cost of small BS (or Wi-Fi BS), $\mathcal{E}_{SPECTRUM}$ is the total discounted cost for spectrum licenses, A_{syst} is the coverage area of entire operator's network and N_M and N_S is the average number of MaBSs and small BSs, respectively.

3.1. Base station unit cost estimates

In line with [3] the total CAPEX for deployment new MaBs is 120 k€. Out of [1], we consider the price of a MiBS and PBS. According to [4], on average the deployment of one FBS is around 1 k€. IEEE 802.11ac access points (AP) products for consumers are currently available at prices of around 160 € [24]. Nevertheless, for the enterprise solutions there should be used WLAN carrier grade access [25, 26]). According to [1] we assume that carrier grade access point supporting IEEE 802.11ac will cost around 1.5 k€, and additional 1k€ should be added per AP, assuming that the control equipment is divided between 20 APs. Based on [3] we assume 30 k€ OPEX for the new MaBS site. Based on [1] we consider 13.4 k€ OPEX for the single carrier MaBS and we apply ratios of 1.15, 1.29, 0.67, 0.21 and 0.10 related to this cost for the 2-carrier MaBS, 3-carrier MaBS, MiBS, PBS and Wi-Fi BS. According to [3], we assume 10 k€ for the existing site. For the FBS, authors in [3] estimates the annual operational cost to be 0.5 k€ per BS. The resulting discounted cost per the considered newly deployed BS class based on (3) is outlined in Table 2.

3.2. Spectrum cost analysis

Within the few forthcoming years, it is expected the sale of the 2x30 MHz spectrum in the 700 band (703-733 MHz & 758-788 MHz). Based on the benchmark analysis [26], the average annual frequency fee per MHz, in 790 MHz to 862 MHz (DD I) band, is below 1 EUR/MHz/population and maximum 10 EUR/MHz/km². According to [27], the invested price in DD I per MHz/population ranges from 0.2 € in Croatia to 0.8 € in Italy.

Table 2. CAPEX, OPEX and Resulting Discounted Cost Estimates per Base Station Class for Greenfield Deployment (all amounts in [k€]).

LTE-A BS and IEEE 802.11ac AP Classes	CAPEX	OPEX	Total Cost
Macro (1 carrier)	72.9	15.5	152.67
Macro (2 carriers)	96.2	17.8	186.47
Macro (3 carriers)	120.0	20.0	220.15
Micro	35.8	10.4	90.73
Pico	13.5	3.4	31.26
Femto	1.0	0.5	3.72
Wi-Fi	2.5	1.6	12.17

4. Investment Case Study

4.1. Case study description

We consider building of the new office center in the 1 km² urban indoor area through construction of ten 5 floor buildings hosting 10.000 workers. Consequently, we will not analyze the MiBS and PBS options, but only the strict indoor solution of small cells represented by FBS alongside with the Wi-Fi. We ignore the cost inputs for the spectrum in (4), since the cost of 1 MHz per the system area of 1 km² is insignificant.

4.2. Traffic demand

In line with [28, 29], we assume that the average usage per month in 2018 will be around 12.2 GB and 6.9 GB for tablets and laptops, respectively. Consequently, we perform the network dimensioning with moderate (44 GB) and high (110 GB) demand of user/month. We consider usage spread over 8 hours per day, translating into a busy hour rate of 12.5% [30]. Conversion of the load to the user data rates and capacity is given in Table 3.

4.3. Macro cellular deployments

Assuming the spectral efficiency of 3.8 bit/s/Hz/cell of outdoor LTE-A RAT, the achieved capacity with a single carrier three-sector MaBS site is 114.0 Mbps, 228.0 Mbps and 342.0 Mbps with 10 MHz, 20 MHz and 30 MHz of spectrum, respectively (calculated in line with (2)).

4.3.1. Macro cellular deployments

Since a cell area of 1 km² corresponds to a cell radius of 0.57 km (1), in line with [11] our requirements on average user data rates during busy hours (~ 1.0 Mbps) would be met even at the cell borders. With the initial scenario, we perform the cost-capacity analysis using 20 MHz for the macro-layer in the 2.6 GHz band with the LTE-A RAT. In accordance with [3], for the MaBS site re-use scenario, we estimate the total CAPEX of 20 k€ for existing site. Table 4 summarizes the total investment costs.

4.3.2. Impact of the Propagation Losses and Wall Penetration Losses Compensation Scenario

According to [3, 4], we consider building a denser network in the 2.6 GHz band and utilization of 10 MHz spectrum in the 700 MHz band in order to ensure better indoor coverage. According to [31] and assuming carrier frequency of 2.6 GHz, the path loss (PL) for the metropolitan cell with range d (in km), could be calculated using the Okumura-Hata propagation model (5).

Table 3. Conversion of Load/User/Month to the User Data Rates (Mbps) and Capacity Per Area Unit (Gbps/km²).

Demand	GB/user/month	Mbps/user	Gbps/km ²
Moderate	44.0	0.407	4.0
High	110.0	1.019	10.0

Table 4. Investments and capacity (Macro sites initial deployment - Case 1).

Macro Initial Scenario (2.6 GHz)		Number of sites	Total CAPEX (M€)	Capacity (Gbps)
Site	Demand			
New	Moderate	18	2.16	4.1
New	High	44	5.3	10.03
Reuse	Moderate	18	0.36	4.1
Reuse	High	44	0.88	10.03

Thus, for the considered cell range of $d = 0.57$ km, we yield $PL = 121.14$ dB, assuming that wall penetration losses do not exceed the 20dB assumed in the initial scenario.

$$PL = 129.73 + 35.20 \log_{10}(d) \quad (5)$$

Based on the Okumura-Hata propagation model, Fig.1 depicts the propagation loss and distance curves for the dense urban environment. It can be seen that the difference between operation in the 700 MHz and the 2.6 GHz band is around 20 dB. If no 700 MHz band is available, the MNO should deploy denser network in 2.6 GHz band to compensate for additional wall attenuation (W), with cell range calculated as follows:

$$d = 10^{\frac{PL-129.73-W}{35.20}} \quad (6)$$

If we assume that we need to compensate for additional $W = 20$ dB wall attenuation due to special construction material, in our case, for $PL = 121.14$ dB, we yield that 3.8 time denser MaBS network should be deployed in the 2.6 GHz band. The cost-capacity outcomes for this scenario are summarized within the Table 5.

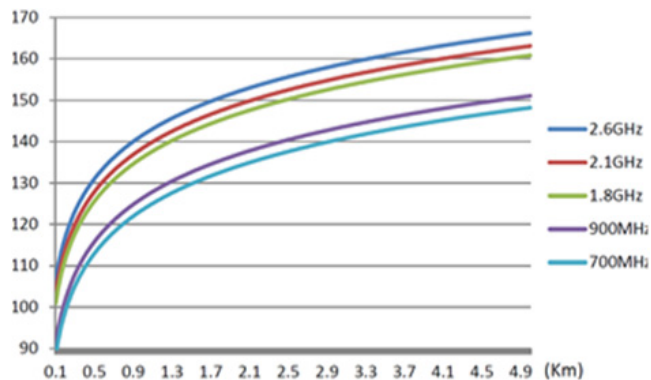


Fig. 1. Free space propagation loss and propagation distance curve comparison in dense urban areas [32].

Table 5. Investments and capacity (Macro sites wall losses compensation deployment - Case 2).

Macro Wall Losses Compensation (0.7 or 2.6 GHz)		Number of sites	Total CAPEX (M€)	Capacity (Gbps)
Site	Demand			
New 0.7 GHz	Mod.	36	4.32	4.1
New 0.7GHz	High.	88	10.56	10.03
Reuse 0.7 GHz	Mod.	36	0.72	4.1
Reuse 0.7 GHz	High.	88	1.76	10.03
New 3.8 x 2.6 GHz	Mod.	69	8.2	15.7
New 3.8 x 2.6 GHz	High.	168	20.1	38.3
Reuse 3.8 x 2.6 GHz	Mod.	69	1.4	15.7
Reuse 3.8 x 2.6 GHz	High.	168	3.4	38.3

Table 6. Investments and capacity (Macro sites with carrier aggregation - Case 3).

Macro Carrier Aggregation (0.7 & 2.6 GHz)		Number of sites	Total CAPEX (M€)	Capacity (Gbps)
Site	Demand			
New	Moderate	12	1.56	4.1
New	High	30	3.9	10.26
Reuse	Moderate	12	0.36	4.1
Reuse	High	30	0.9	10.26

4.3.3. Carrier Aggregation Scenario

This scenario considers aggregation of the both frequency carriers at 700 MHz and 2.6 GHz bands. By this, the bandwidth will be increased to 30 MHz, and exactly this is going to be the solution how to increase the capacity (even for 3 times) compared to the use of only 10 MHz bandwidth in 700 MHz band, but without increase the number of sites due to coverage reasons with 2.6 GHz band. Results are summarized in the Table 6.

4.3.4. Femto cell and Wi-Fi deployments

In line with [3], and explanations for the maximum numbers of users per access point for FBS and Wi-Fi given in Section II above, we consider different greenfield options of the user oriented and coverage oriented approaches. The Table 7 summarizes the related cost-capacity figures.

5. Comparative Cost-Capacity Discussions

We compare in Fig. 2 the investment costs for separate network deployments as function of user demand. LTE-A MaBS deployment with site re-use and carrier aggregation in place, has the lowest cost for the capacities below 2.0 Gbps. The LTE-A RAT carrier aggregation functionality could be acceptable MaBS deployment scenario for the new market entrant for high demand levels. The reuse of the existing MaBS with 10 MHz spectrum in the 700 MHz band causes achieving high demand with tolerable investment of 1.76 M€ due to the superb penetration performance of the 700 MHz carrier frequency. Denser network deployments of 4 users per FBS/Wi-Fi or 32 FBS/Wi-Fi sites per floor, are less cost-effective options comparing to most of the MaBS deployments for less than 6.5 Gbps. FBS/Wi-Fi deployments are most cost-efficient when single site can support higher number of users (e.g. 32 per site or 4 sites per floor).

Fig. 3 shows the graphical representation of the total discounted cost for various heterogeneous network deployments in 10 years period. The results are yield for the high demand level of 10 Gbps/km². Having in mind that some of the FBS and Wi-Fi options produce capacity overprovisioning (e.g. 4-8 user per BS or 16-32 BS per floor), we combine some of those deployments only with the initial MaBS scenario. An MNO having deployed macro network with 20 MHz in the 2.6 GHz network, instead of investing in additional spectrum or deploying denser network, could compensate the indoor wall penetration losses by deploying 16 FBS sites per floor. That total discounted of around 6.0 M€ is comparable for instance with deployment of new MaBS sites with carrier aggregation and 32 users per FBS indoor deployment what in fact is the most cost efficient combined macro/small cell deployment for still acceptable user satisfaction from the capacity perspective.

Table 7. Investments and capacity (FBS LTE-A based and Wi-Fi IEEE 802.11ac deployments).

Femto Cells and Wi-Fi	No. of sites		CAPEX (M€)		Capacity (Gbps)	
	FBS	Wi-Fi	FBS	Wi-Fi	FBS	Wi-Fi
4 users / BS	2500	2500	2.5	6.25	330	3250
8 users / BS	1250	1250	1.25	3.13	165	1625
16 users / BS	625	625	0.63	1.56	82.5	812.5
32 users / BS	313	313	0.32	0.78	41.3	406.9
4 BS / floor	200	200	0.2	0.5	26.4	260
8 BS / floor	400	400	0.4	1.0	52.8	520
16 BS / floor	800	800	0.8	2.0	105.6	1040
32 BS / floor	1600	1600	1.6	4.00	211.2	2080

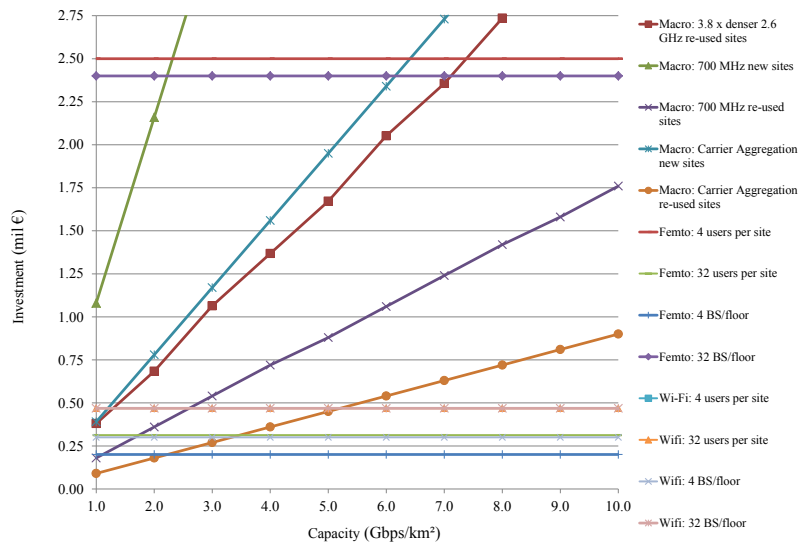


Fig. 2. Comparison of macro and small cell deployment costs as function of the user demand.

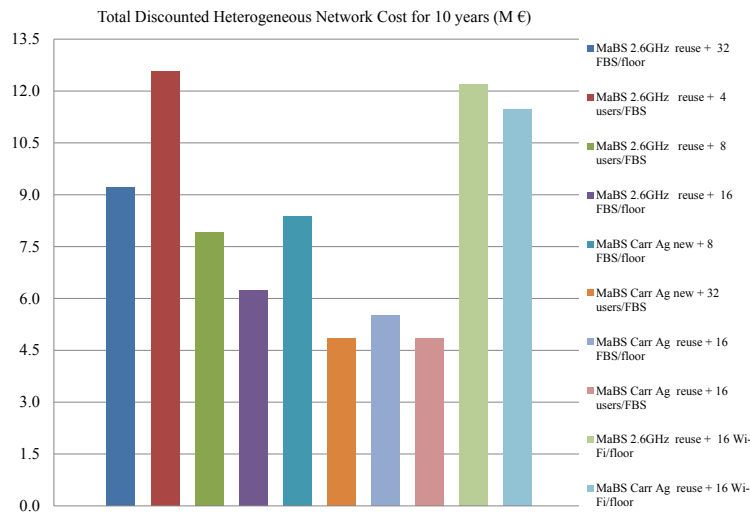


Fig. 3. Wireless heterogeneous network total discounted cost for 10 years (deployments aim to satisfy high demand level of 10 Gbps/km²).

6. Conclusion

We propose a model for evaluation of the total deployment costs of heterogeneous wireless access network using LTE-Advanced and IEEE 802.11ac standard. The model uses up to date inputs of the unit cost of particular base station class which is characterized with specific coverage and capacity parameters. Through the investment case study we analyzed macro and small celss deployments in the 700 MHz and 2.6 GHz bands as well as the

scenario of aggregated carriers. The key finding is that with enabling aggregation of the carriers in the band of 700 MHz and of 2.6 GHz on the existing sites we create the most cost-efficient deployment for moderate demand levels. Also, macro cell deployment scenarios show linear increase with demand. The indoor deployed femto cell and Wi-Fi solutions are most cost efficient only for the extreme user demands. Results indicate that FBS/Wi-Fi significantly become cost-efficient when single site can support higher number of users, due to the very low unit cost compared to the equipment cost of the higher order cellular deployments. For the high demand levels, the joint heterogeneous deployment determines that operator holding less spectrum, could compensate the indoor wall penetration losses by deploying the acceptable number of FBS sites per floor.

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